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A SYSTEM FOR GENERATING A FLOWING GAS CONCENTRATION SIGNAL.(U)

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Abstract

The theory, design, and performance of a computer-controlled gas sampling system, utilizing a linear electric motor to pump a liquid metal for the generation of concentration input signals, is presented. Computer control of the current passing through mercury droplets interspaced by gas samples enables control of the amplitude and frequency (1-10 hertz range) of the concentration profile. The system is discussed in terms of the advantages of reproducibility, reliability, and speed resulting from a design with no moving parts. Possible applications in analytical chemistry are numerous, but cross-correlation and other multiple injection chromatographic experiments are of current interest to the authors.

INTRODUCTION

A single injection input to a chromatographic column is not the only kind of input signal which may be useful in chromatographic experiments. It is just the simplest and by far the most widely used input signal whether generated by syringe or any one of a variety of mechanical sampling valves. A large number of other input signals may be of value in new kinds of chromatographic methods. Reilley, et. al. (1) proposed several different input signals for chromatographic columns but experimented only with variations of the single impulse and step signals because no general signal transducer was available to them. Hiratsuka and Ichikawa (2) succeeded in inputting a sinusoidal signal to a chromatographic column by switching back and forth between two streams of different concentration and then attenuating all but the fundamental frequency in a large dead volume. Pseudorandom signals required for cross correlation chromatography (3-5) can be generated using a mechanical sampling valve of the type designed for single injections and firing it repeated under the control of a computer programmed pseudorandom number generator.

In all of the above examples, some means is required to generate flowing gas stream concentration change signals more complex than the easy to generate single impulse or step change signals. This general problem has not yet been solved and a solution for it would make many new and potentially useful chromatographic techniques practical.

It is possible to generate more complex chromatographic input signals by overlapping large numbers of single injections using a mechanical sampling valve. However, after a few thousand injections, valves with mechanical seals tend to break down as the seals wear out and have to be replaced. Also, some valves of this type are not 100% reliable. For example, a gas

pressure activated Carle valve used for cross correlation experiments would occasionally jam and miss an injection. This is not a serious problem for single injection chromatography because it doesn't happen very often and when it does the consequences are obvious. But, for cross correlation experiments with hundreds or thousands of injections, mis-firing on a few percent of the injections can ruin the results. Thus, it was necessary in all of these experiments done using the Carle injection valve to tune up and test the valve before each experiment and watch it during the experiment.

The second major limitation of mechanical gas sampling valves is their slow cycle time. For the Carle valve the maximum reliable firing rate is about 2 Hz and the actual time of an injection is probably not accurate to better than 0.1 second. The frequencies contained in signals produced by combining individual injections must be less than this. Cross correlation experiments with a thousand or more injections can take hours to run. Some potentially interesting experiments using short retention time columns (less than about 30 seconds) cannot be run at all.

It is probably possible to build a mechanical valve that can move considerably faster than the Carle valve used previously. However, just moving faster is not enough, if the concentration signal produced by an individual injection does not contain frequency components at least as high as the maximum injection frequency, then multiple injections will merge resulting in no concentration signal at the higher frequencies. The extra speed is then of no value. As the speed of a valve is increased, more attention must be given to dead volume and mixing since they ultimately limit the high frequency response of any concentration signal transducer.

Some mechanical valves designed for chromatographic work are advertised as having "zero" dead volume. Of course the internal volume of the valve is not really zero. What is really meant by this statement is that the internal volume is the same as an equivalent length of connecting tubing. The mixing produced by firing the valve may be a more serious limitation and it is usually ignored. All of these valves work by sliding some kind of mechanical seal to open and close passage ways for carrier and sample gas. When the valve is fired the uniformly flowing gases are interrupted for a short period of time as the seal moves. Locally the pressure and flow rates must change drastically. After the valve has been fired, it will take some additional time for the gas flows to stabilize again. Thus the system is disturbed for at least as long as it takes to fire the valve. These kinds of disturbances will result in turbulent gas flow and, in some designs, reversed gas flow for a period of time inversely related to the maximum switching frequency of the valve. How the turbulent mixing is affected by these disturbances to the gas flow is very difficult to work out in detail, but there must be some turbulent mixing over the period of the sampling valve firing and it will limit the frequency response of the sampling system to something less than the maximum switching frequency of the valve.

A new kind of high speed gas injection valve is needed for cross correlation experiments and complex input signal chromatography in general. The minimum requirements for such a valve are that it be significantly faster and more reliable than the commercially available valves and be able to generate a suitably random input signal under the control of the computer. Any design using a mechanical seal is not likely to be successful because of the break down problem and limitations in sampling frequency.

Wade and Cram (6) built a fluidics gas injection valve using commercially available components. Fluidics is analogous to electronics except instead of electrons flowing through conductors, gases are flowing through holes (7,8). Analogous components (e.g. resistors, capacitors, diodes, etc.) can be combined to make fluidic circuits. It is fairly easy to design a device which on command injects a sample of one gas stream into another. However, the situation is not quite as simple as it seems. Fluidics components are not as well behaved as electronics and often do not work exactly as expected. Most commonly they are designed for use with compressed air at 5 psi. With other gases and pressures problems arise and extra components have to be added to fix them. Even then a fluidics circuit is delicate and somewhat difficult to use.

Some of the problems with fluidics could be solved by redesigning the components to work under the conditions expected at the head of a gas chromatography column. This would be difficult to do because the theory of turbulent gas flow through small holes can be quite complex (9). It would be even worse if the valve has to be designed to work under various conditions of pressure and flow rate with different columns.

System Design

A new kind of gas injection valve has been built using a liquid seal. The liquid is mercury which in the form of small drops makes a moveable seal inside a thin teflon tube. The mercury drops are controlled by an external magnetic field and an electric current flowing through the drops as illustrated in Figure 1.

This device is essentially a linear direct current motor and like all electric motors is based on the principle that a force can be generated

through the interaction of a magnetic field and an electric current (10).

$$\vec{F} = i\vec{l} \times \vec{B} \quad (1)$$

In the above equation, the force, F , generated between the magnetic field and the current is equal to the cross product of the current, i , and the magnetic field, B , times the length of the conductor in the magnetic field.

The current flows across the diameter of the tube, a distance of twice the radius, r , at a right angle to the magnetic field. Therefore the force generated on each mercury drop in the direction of flow is given by equation 2.

$$F = 2riB \quad (2)$$

Pressure is defined to be force per unit area or

$$P = F/\pi r^2. \quad (3)$$

If there are n drops of mercury inside the magnetic field simultaneously each carrying the same current, then the total pressure generated by the valve is

$$P = 2niB/\pi r. \quad (4)$$

Devices based on these principles have been previously used to pump

liquid metals, particularly in liquid metal cooled nuclear reactors (11-12). Of course, pumps for this application are much larger and are of little value in designing a small laboratory device like this injection valve. Smaller scale electromagnetic liquid metal pumps have been applied to research studies of the reactions of alkali metals (13-15). In this application a pump is needed to produce a stream of liquid metal with a fresh surface to react with a gas. Panholzer (16) has reviewed the various types of electromagnetic pumps and the principles of their operation.

The electric current can be varied to change the pressure causing the mercury drops to move in the tube. Thus, the mercury drops form easily controlled moveable seals between small samples of gas.

The samples of gas between the mercury drops are to be injected into a chromatographic column as the input signal for a cross correlation or other complex input signal experiment. It is required that the samples be uniform in size in order to produce a controllable and reproduceable signal. The mercury drops should also be uniform in size so that the number of them in the magnetic field will remain constant.

A very simple but effective way to produce uniform mercury drops and gas samples is to combine the two uniformly flowing streams in a tee connection. The relative sizes of the samples and drops is determined by the relative flow rates of gas and mercury. Within limits set by the viscosity and surface tension of mercury, the size of the drops is determined by the internal diameter of the tee connection.

The only significant problem with this technique of producing uniform samples is in maintaining constant flow rates for the gas and mercury streams. A commercially available flow controller helps on the gas stream, but because of the compressability of the gas, any significant volume

between the flow controller and the tee can cause short term instability if the pressure at the tee should change. Therefore, tubing connecting the flow controller to the tee should be kept short and the pressure at the tee should be kept as constant as possible.

The mercury stream flow rate can be kept constant by putting it under fairly high pressure and placing a restriction in the line just before the tee. The flow rate is then mostly determined by the restriction. Any other effects such as a small change in pressure at the tee will make little difference in the flow rate.

The tee connection produces samples at a constant rate, but in order to produce a signal they must be injected into the column at a variable rate. The tee cannot be connected directly to the magnet because the pressure changes at the magnet inlet caused by the varying current signal would adversely affect sample size uniformity without achieving the desired variation in sample injection rate. The solution to this problem is to provide a buffer between the tee connection and the magnet so that the uniform rate of sample production can be matched to the average rate of sample consumption. A length of Teflon tubing connecting them together will act as a buffer saving up samples until needed, or alternately as a filter, damping out high frequency pressure changes before they can reach the tee. The gas samples in the tube are compressable so they have a capacitance, while the moving mercury drops have a frictional resistance, resulting in a damping effect analogous to an electronic RC filter.

The gas sample stream as it enters the tee connection is composed of carrier gas for the chromatographic experiment with a small concentration of a sample substance. The simplest way to get a constant low concentration

in a constantly flowing stream is with a gas diffusion cell (17). For this sampling valve it must be placed in the line before the flow controller because of the need to limit the volume between the flow controller and the tee connection. The upstream side of the flow controller must be under higher pressure (about 100 psi) for the flow controller to work properly. At this high pressure adjustment of the sample level in the capillary tube by means of a stopcock and squeeze bulb as in (17) is not feasible. For reliable operation the whole diffusion cell must be tightly sealed at the operating pressure. Sample size is determined by the gas flow rate, the temperature, and the level of the sample in the capillary.

After a sample leaves the magnet, it must be separated from the mercury drop preceeding it and be injected into the carrier gas stream flowing into the chromatographic column. This can be done using the device shown in Figure 2. The gas-mercury drop stream enters the device through a stainless steel tube at the top. The stream passes through the tube into a small mercury reservoir at the bottom. The mercury in this reservoir is under a small pressure relative to the surrounding gas because the mercury exit is at a higher level than the reservoir. Carrier gas for the chromatographic column flows from the surrounding volume, through the device, and out through a connecting tube. The sample gas is injected into the carrier steam by flowing through a snug, but not gas tight connection between the outside of a piece of Teflon tubing slipped over the stainless steel entrance tube and a hole drilled in the polyethelene body of the device. The slight pressure in the mercury reservoir forces any gas samples which enter it to leak out into the carrier stream flowing by. The surface tension of mercury is sufficient to keep it from leaking through into the carrier. Mercury

drops entering the reservoir simply displace an equal volume of mercury which falls out of the reservoir exit hole and accumulates at the bottom of the 500 ml flask from which it can be removed periodically through a drainage tube for recycling. It is important that the pressure remain constant inside this chamber in order to maintain a constant flow rate through the chromatographic column.

It is not required that the computer control each individual injection of the input signal for a cross correlation chromatography experiment. It is only necessary that the signal be sufficiently random and that the computer knows what it is. The requirements can be satisfied by providing the computer with a single input line which causes an interrupt every time a gas sample flows by and with a digital to analog converter controlling the current through the mercury drops. The computer then can generate a signal and note the time at which each injection occurs.

When operated in this fashion, the valve behaves more like a general signal transducer than an injective valve. It takes an electronic signal supplied by the computer and makes a copy of it as a concentration signal in a flowing gas stream. If the individual gas samples come fast enough, then they merge together to make a continuous signal proportional to the rate of injection.

The actual signal input to the column, as measured by the rate of sample injection, will not be the same as the signal sent to the injection valve by the computer. The valve is a signal transducer which acts like a band pass filter whose low frequency cut off is determined by the limited capacity of the buffer tubing between the tee and the magnet and high frequency cut off by the dead volume of the injection section and connecting

tubing. No frequencies higher than the dead volume cut off will make it into the column and the computer should not attempt to generate any frequencies too low or else they will get through the buffer tubing and cause changes in sample drop size.

System Construction

An overall diagram of the high speed gas injection valve is given in Figures 3-5. The various parts of the valve have evolved from numerous earlier versions and further improvements could be made. Its construction is most naturally divided into three sections: the drop maker, the linear DC motor, and the injector.

The drop maker section, shown in Figure 3, includes the constant flow sample stream, constant flow mercury stream, tee connection, and buffer tubing. It produces uniform samples of gas separated by mercury and delivers them to the magnet section on demand, but at an average rate equal to the rate of production.

From the pressure regulator on the gas supply cylinder, the pure sample carrier gas flows to a diffusion cell for the introduction of a low concentration of whatever the sample substance is to be. The diffusion cell, shown in Figure 3, is made of 1/4 inch OD glass tubing about 15 cm long connected at each end to 1/8 inch OD copper tubing with Teflon swaglock connectors. Suspended inside by a small plug of glass wool is an ordinary melting point determination glass capillary tube with a liquid sample. The liquid level in the capillary determines the sample size. From the diffusion cell, the gas plus sample flows through the flow controller (Brooks) to the tee connector.

The mercury supply is kept in a leveling bulb suspended on a tower about 2 m above the table. The mercury flows through a thick walled Teflon tube to a stopcock (Hamilton) mounted just below the level of the tee connector. Thick walled tubing was used here to reduce the chances of a disastrous mercury leak. From the stopcock, the mercury flows through a restrictor to the tee connector. A piece of copper wire about 2 cm long fitted snugly inside the Teflon tube carrying the mercury makes an excellent restrictor.

The tee connector is made from a small block of Teflon with the tee drilled inside it. The holes are 1/16 inch diameter which is about the same as the inside diameter of the Teflon buffer tubing. Connections are made to the three branches of the tee by pushing snug fitting 1/16 inch OD stainless steel tubing into the holes and then applying epoxy to the outside around the holes for extra strength. The mercury line is connected to the downward pointing branch of the tee so that it will flow up to and be swept into the gas stream. It is important that all air bubbles be removed from the mercury stream between the restrictor and tee. The mercury inlet and the drop outlet branches of the tee connect to Teflon tubing by slipping the tubes over the 1/16 inch stainless steel tubing connectors and sealing the connection with heat shrink tubing. The buffer tube is made of a piece of 1/16 inch ID thick walled Teflon tubing about 310 cm long wrapped around a 15 cm diameter cylinder. Gas samples separated by mercury drops flow into the tube at a constant rate at one end and flow out at a variable rate controlled by the signal from the computer at the other end. High frequency fluctuations in flow rate are damped out by the buffer capacity of the tube before they reach the tee connection.

The detailed behavior of the buffer is quite complex. First, there is a pressure drop along it caused by the frictional resistance to flow of the mercury drops against the Teflon tube walls. Because of the pressure difference the volume of the gas samples is larger at the low pressure magnet end of the tube than at the tee connection. And, because of the larger volume of gas at the magnet end of the buffer tube, the mercury drops and gas samples must flow through the tube faster. But, above a certain speed, the mercury drops can suddenly break loose from the tube walls. This greatly reduces their frictional resistance so that more mercury drops move faster until they also reach the critical speed and break loose. The process can continue until the whole buffer tube full of drops becomes unstable with disastrous results for any experiment in progress. There is an upper limit in sample flow rate which should not be exceeded at any time. At the tee connection end of the buffer tube, the gas samples are compressed into a small volume by the pressure drop along the tube. This creates a problem for the gas flow controller which works best at a moderate flow rates. Also, at even lower flow rates, the gas bubbles between mercury drops would become too small for stability.

It is tempting to improve the low frequency response of the valve by increasing the length of the buffer tube since the buffering capacity is proportional to the square of its length. But to do so, either the gas volume and flow rate at the magnet end of the tube must be increased, or the gas volume and flow rate through the flow controller must be decreased. There are limits on both ends, so with the presently available equipment, the buffer tube length could be increased only a moderate amount.

Mercury drops flowing through a Teflon tube are excellent static electricity generators. If nothing is done to control this static then

sparking will occur among the mercury drops and between the tube and outside metal objects. This causes very erratic buffer tube behavior and may even disrupt the computer's electronics. The solution is to use a grounded metal cylinder, a large coffee can is about right, to wrap the Teflon buffer tube around. Even with this, however, there may still be a spark when the mercury flow is first turned on especially if the mercury is turned on before the sample gas producing a very long first drop.

The linear DC motor section, as shown in Figure 4, contains the electro-magnet, the tube to make electrical contact with the mercury drops, power supplies, and computer interface electronics. It accepts an input signal from the computer and uses it to control the rate at which gas samples pass through. Each sample passing through generates an interrupt signal which is returned to the computer.

The sample stream passes through the magnet inside a thin-walled Teflon tube 1/16 inch OD, which is strung with 36 guage copper wire to make electrical contact with the mercury drops. The outside of the tube is coated with a layer of epoxy to seal holes made for the copper wire to enter the tube. The epoxy is allowed to harden inside the magnet so that its shape will conform to the shape of the magnet poles providing a stable support for the tube.

The copper wire is sewn through holes in the Teflon tube in the pattern illustrated by Figure 6. There are actually two wires, one for each side of the tube, which together form a circle of copper tightly pressed against the inside of the Teflon tube. Outside the tube, the wires return to the other side of the tube to re-enter it and make another circle of copper 0.200 inch down the tube. The pattern is repeated 24 times along the whole

length of the tube between the magnet poles.

As can be seen in Figure 6, a current passing through the copper wires will repeatedly cross through the tube in the same direction. The average current inside the tube crosses the tube at right angles to the magnetic field B. According to equation 1, this will produce a net force at right angles to both the average current and the magnetic field, that is along the length of the tube. The wires are firmly attached to the tube which is attached to the magnet so no movement can result from the force on the current in the wires. However, if a mercury drop is in contact with a circle of copper inside the tube, then most of the current will flow through it instead of the wire. The electrical conductivity of mercury is considerably less than that of copper, but in a mercury drop the cross sectional area available to the current is so much greater that most of the current flows through the mercury whenever it is available. The mercury drops are not attached to the tube so that force exerted on them results in pressure on the drops and the gas samples between them.

Fabrication of the tube with the copper wires sewn through it is a delicate task. The first step is to punch a set of 24 aligned holes .200 inch apart in the Teflon tube. This is best done using a milling machine table for support and alignment. A stiff needle which is a little larger than the copper wire in diameter is clamped into the drill chuck. It does not have to be perfectly vertical since it will not be rotating. A fine needle intended for bead working is best. A guide consisting of a small piece of plexiglass with a horizontal hole for the tube to pass through and, perpendicular to it, a vertical hole just large enough for the needle is needed to be sure the needle punches its holes straight through the middle of the tube. The Teflon tube is clamped to the milling

machine table at each end with the guide slipped over it. Holes are punched through the tube by lowering the drill chuck to press the needle through its hole in the guide.

Next the two wires are sewn through the holes in the tube in the pattern shown in Figure 6. The wires are pushed through a pair of holes across the tube and then separated inside the tube with the point of a needle. A length of 1/16 inch OD stainless steel tubing is used to press the two wires firmly against the inside to the tube forming a circle of copper. The procedure is then repeated for the next pair of holes. Care must be taken not to enlarge the holes any more than necessary or to get any kinks in the copper wire inside the tube. If the holes are too large, liquid epoxy can get inside to coat part of the wire preventing good electrical contact with the mercury. If the copper wire does not form good smooth circles, then it can cause unstable mercury drops resulting in nonuniform sample sizes.

Coating the tube with epoxy should be done carefully so as not to force any of it through the holes. Before the epoxy hardens, the tube must be placed inside the magnet with the copper wires carefully aligned so the current will flow across the tube perpendicular to the field generated by the magnetic poles. The poles should be lined up straight and as close together as possible to maximize the magnetic field strength. Placing a strip of Teflon tape on each pole will keep the epoxy from sticking to them so that the assembly may be taken apart later without destroying the tube.

The wired tube can accept up to 5A of current continuously. A signal is supplied by the computer using a digital to analog converter (HP 6131B).

This voltage signal is used to control the direction and magnitude of the current passing through the mercury drops by means of a current amplifier circuit. Power is required at $\pm 15V$ with up to 5A.

The magnet is constructed from 1/2 inch cold rolled steel plate except for the poles which are Armco magnet steel. The magnet windings are 24 guage coated copper wire with approximately 800 turns on each pole. It uses 1.4A at 36VDC supplied by a constant current regulated power supply.

The time at which individual gas samples enter the carrier can be observed with a phototransistor, light emitting diode circuit (18). The amount of light passing through the Teflon tube depends on whether a mercury drop or gas sample is present between the light emitting diode and the phototransistor. This signal can be displayed on an oscilloscope or amplified by the second transistor and sent to an interrupt line on the computer interface.

The mercury-gas separator shown in Figure 2 was machined from two small blocks of polyethylene. The lower piece is just a bottom plate which is glued on to form the mercury reservoir. It is machined separately to allow access to the inside of the reservoir for drilling holes during fabrication of the upper part. The upper piece contains three separate passage ways. The first, and most complicated one, provides an entrance for the mercury-gas sample stream and separates the gas from the mercury. The upper part of this hole is 1/16 inch in diameter and simply holds the 1/16 inch OD stainless steel entrance tube firmly in place. The lower part of this hole is 0.0890 inch in diameter. The entrance tube passes through the center of this hole and on to the mercury reservoir. The space between the entrance tube and the 0.0890 inch walls is filled with a

section of 1/16 inch ID teflon tubing. The mercury flows into the reservoir and the gas leaks around the snug, but not gas tight, Teflon tube into the second passage way through which carrier gas is flowing. The carrier gas stream enters this passage way from the surrounding gas through a 0.0420 inch hole. Just before the passage reaches the junction with the sample separation passage, it is expanded to 1/16 inch diameter. At the junction, the internal diameter is the 0.0890 inch size of the entrance-separation passage way. The carrier gas flows through this junction passing on either side of the stainless steel entrance tube and sweeping any sample gas leaking into the junction along with it. On the other side of the junction, a 1/16 inch OD stainless steel tube is pressed snugly into the hole. It carries the carrier gas stream plus sample directly to the chromatographic column. The third passage way provides an exit for the mercury and determines the pressure difference between the mercury reservoir and the carrier gas stream. It is a vertical hole 1/16 inch in diameter running from the reservoir to an exit hole near the top of the piece.

The two parts are held together with a piece of copper wire and the outside of the junction coated with epoxy for stability. The entrance and exit stainless steel tubes are also held in place with epoxy. The pressure difference between inside and outside is quite small so the epoxy is needed more for rigidity than for sealing purposes. The overall dimensions of the final device must be small enough for it to fit through the neck of a 500ml round bottom flask so the corners were shaved off a little with a razor blade.

System Testing

The completed high speed gas injection valve was tested by connecting its output to a needle valve resistance and a flame ionization detector. A needle valve was used in place of a chromatographic column to provide a realistic back pressure without the complex behavior of a real column. The computer (HP 2115) was provided with a program to generate a repetitive signal whose frequency was selectable from the switch register. The signal was a modified square wave with extra power provided on each positive and negative transition. The extra current passing through the mercury drops during each transition of the square wave allows the linear electric motor to overcome the momentum of the mercury drops more quickly resulting in a better frequency response.

The results of a series of tests for frequencies ranging from 0.61 Hz to 4.88 Hz are given in figures 7-10. In all of these, a signal of the input frequency is present in the output along with a considerable amount of noise. The amplitude of the signal decreases with increasing frequency as expected for a dead volume or mixing limit system.

At the highest frequency tested, 9.77 Hz, the signal is lost in the noise. This is not surprising since the individual gas samples in the mercury-gas sample stream are produced only a little faster than this. A single cycle of this signal would include only one or two individual samples. The large variation in amount of sample injected on each cycle of the input signal would make the output noisy. With a little dead volume or mixing added on to spread the signal out a bit it is easily lost.

The system described is able to generate concentration signals in a flowing gas stream with frequency components in the range of 1 Hz to about 10 Hz. Since the value does alternate the higher and lower frequencies,

the actual signal being introduced to the measurement device should be monitored by means of a phototransistor. The number of mercury drops per unit time is the best measure of the concentration signal.

The physical limitations of this system have been established. The low frequency response is limited by the length (capacity) of the buffer tube. The maximum length of this tube is in turn limited by the pressure drop (resistance) which can be tolerated. A practical limit for this system would appear to be in the order of 600 cm. The high frequency response is ultimately limited by the mixing volume of the gas-mercury separator.

At all frequencies, the output signals were noisy. The major cause of this noise is a lack of uniformity in the mercury drops and the gas samples between them. The tee junction makes very good uniform drops but by the time they get to the gas sample injector some of the mercury drops have allowed gas to leak around them resulting in variations in gas sample size or even the combination of two mercury drops into one. This leaking can occur wherever there is some kind of roughness along the tube. It can happen at connections between sections of tubing, at dirty spots on the walls of the tubes, at kinks in the buffer tube, or at the copper wires inside the tube passing through the magnet. It is very important that all parts in contact with mercury be kept clean and that only clean mercury be used. The situation could be greatly improved by keeping the mercury in a sealed system and automatically recycling it possibly by using gas pressure rather than gravity as a driving force.

An alternative approach to this means of signal generation would be to design a system based on the principle of a linear induction motor. In such

a system, the changing magnetic field induces the required currents in the mercury drops as well as providing a field for the currents to work against. Consequently no external electrical connections to the mercury drops are needed. The greater complexity involved in the design of an induction motor (16) would be compensated for by the possible elimination of many of the sources of noise present in this system.

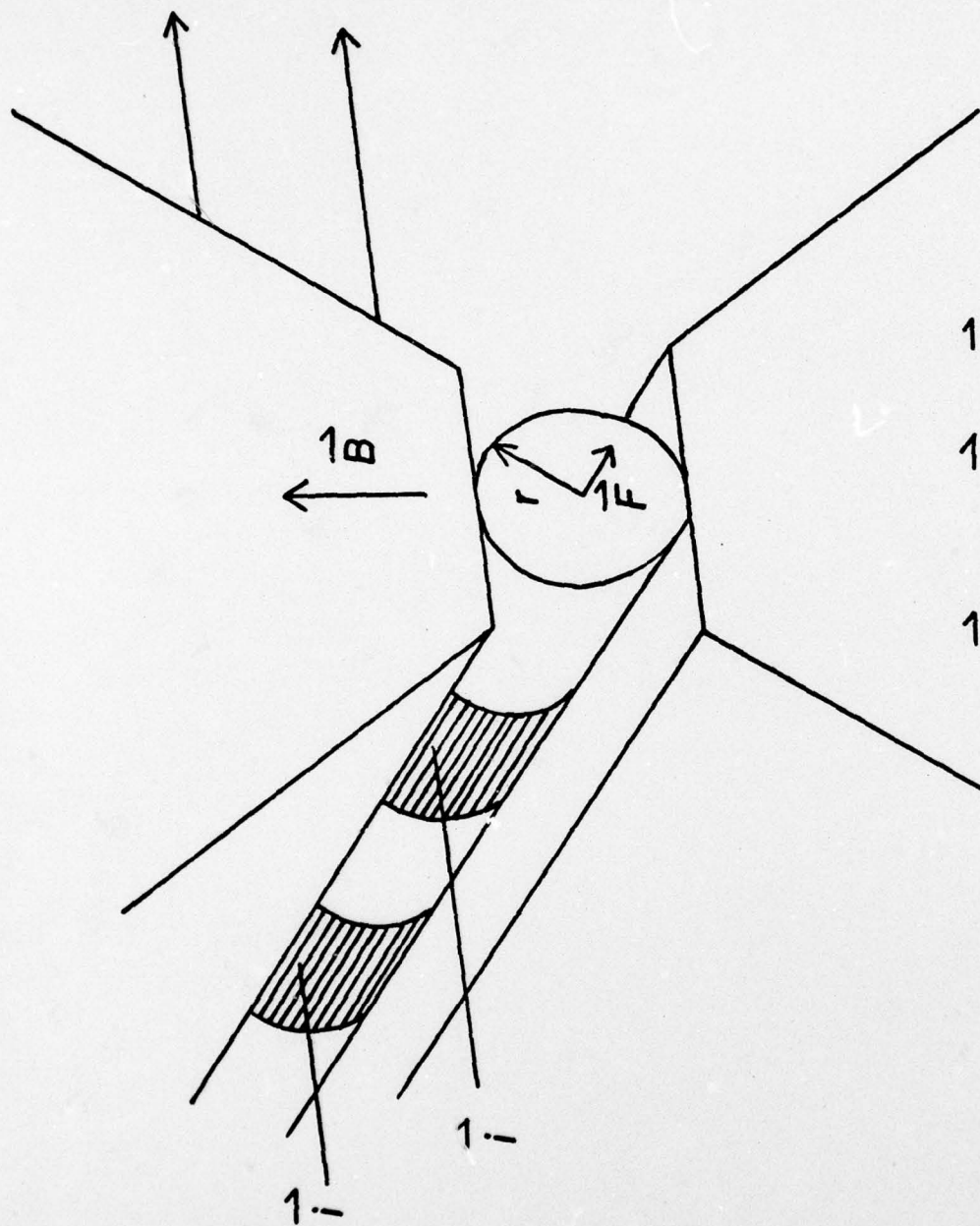
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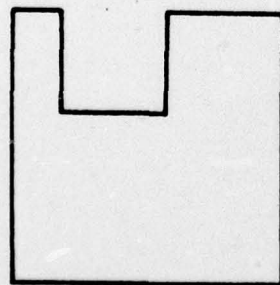
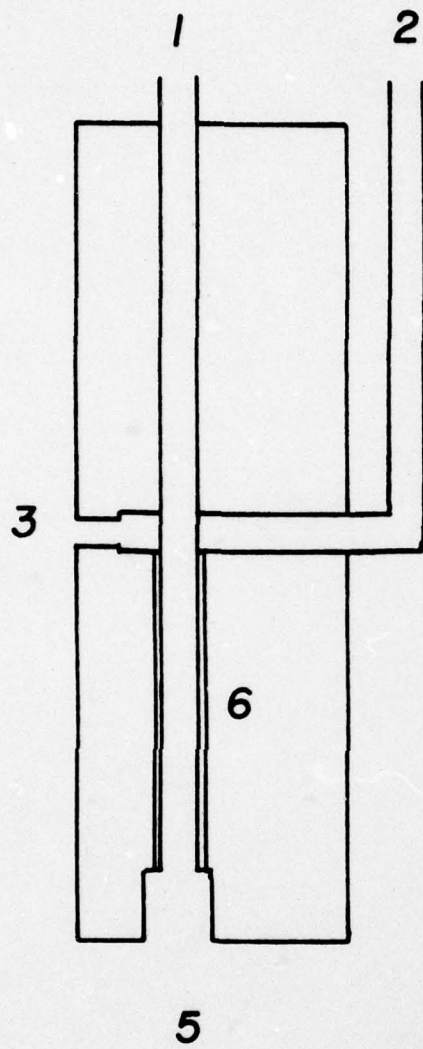
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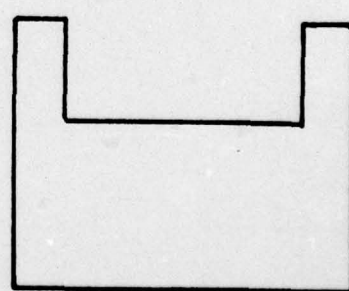
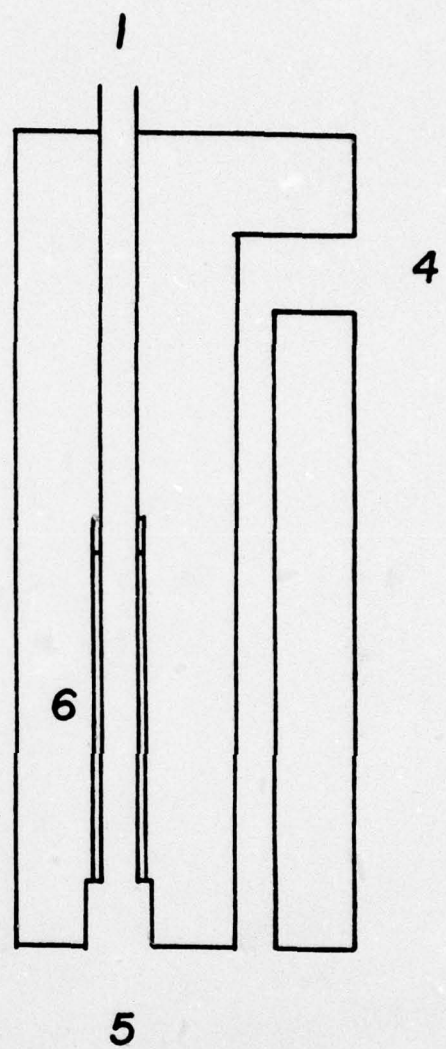
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$$P = \frac{2niB}{\pi r}$$

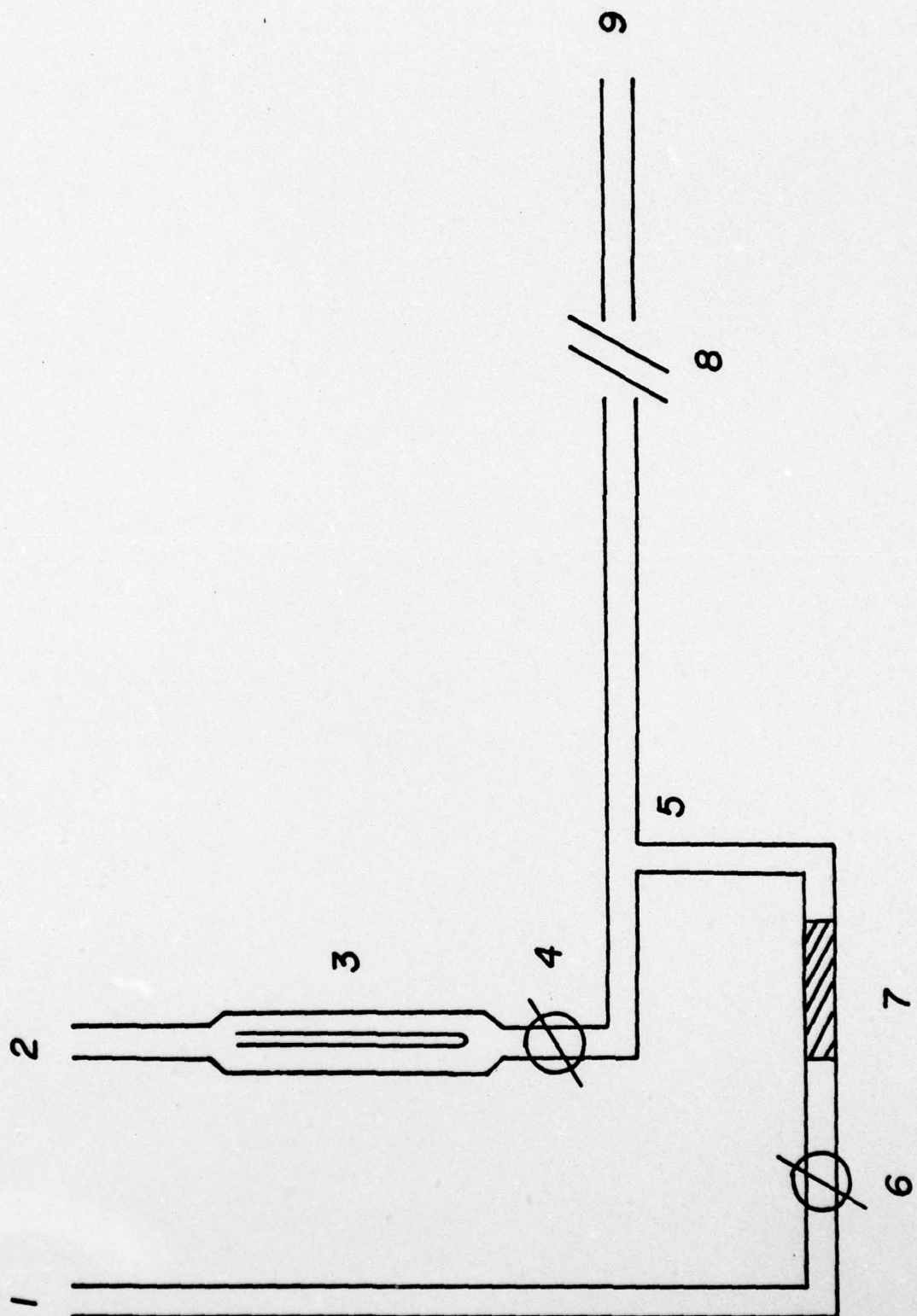
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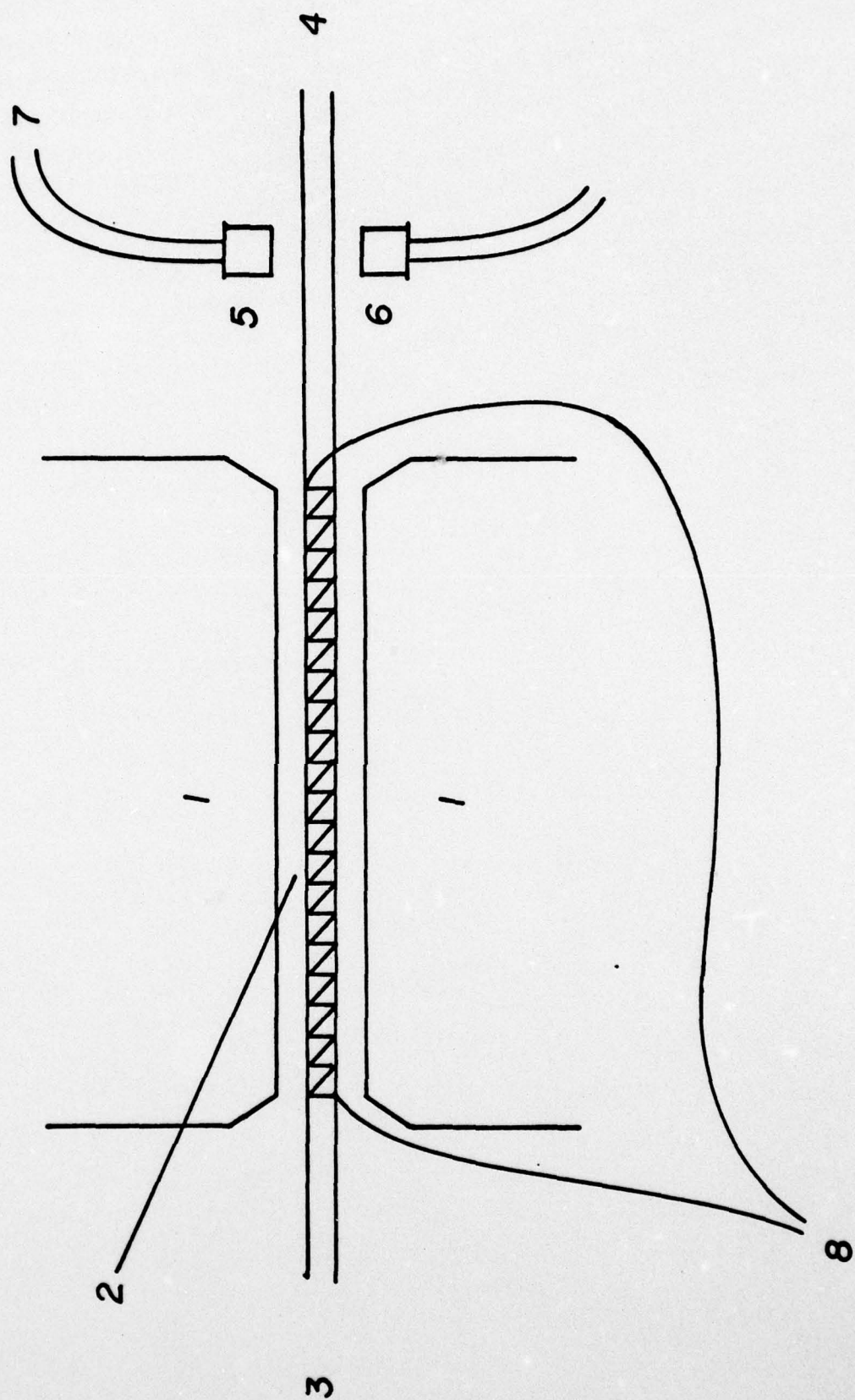


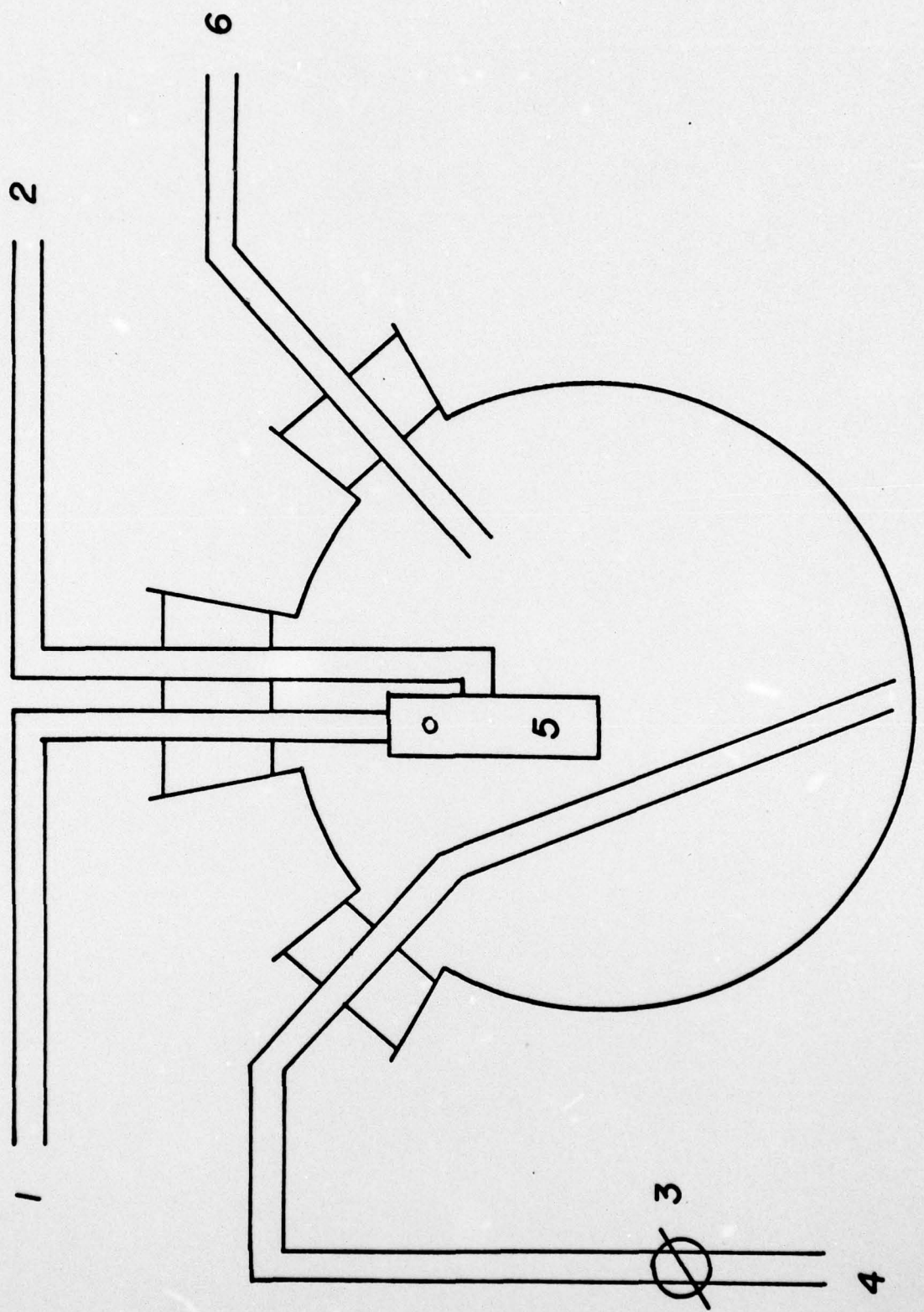
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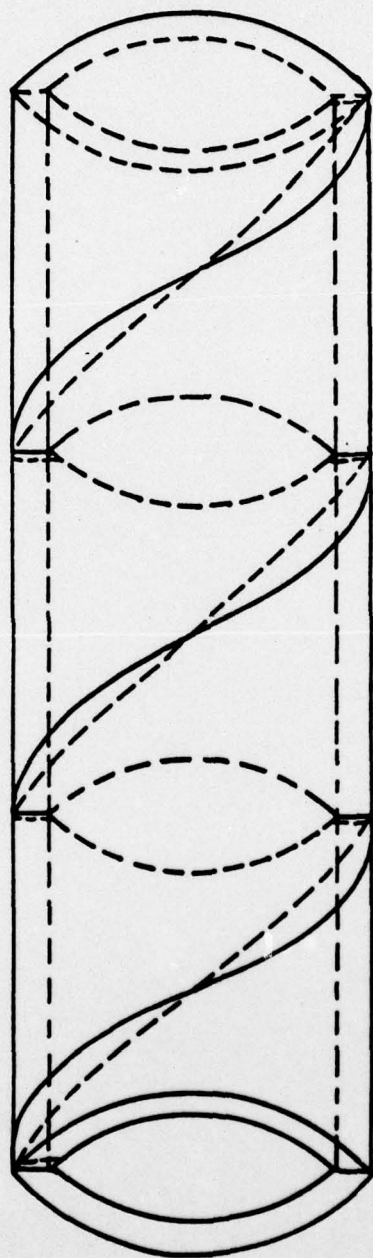


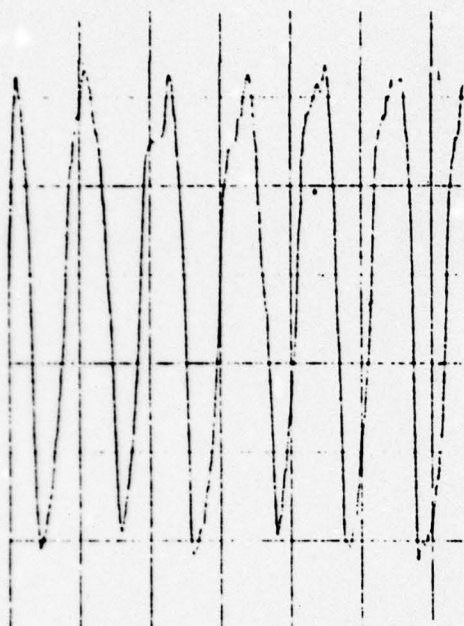
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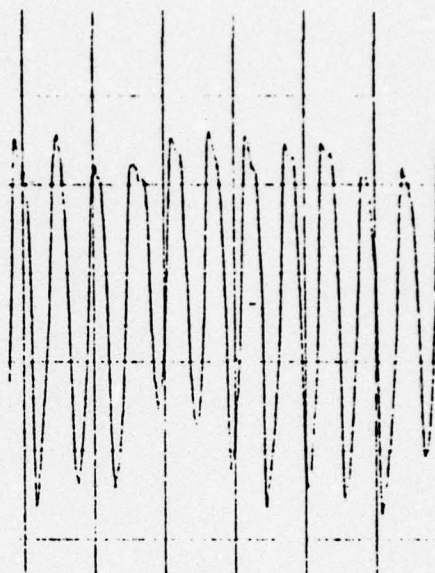




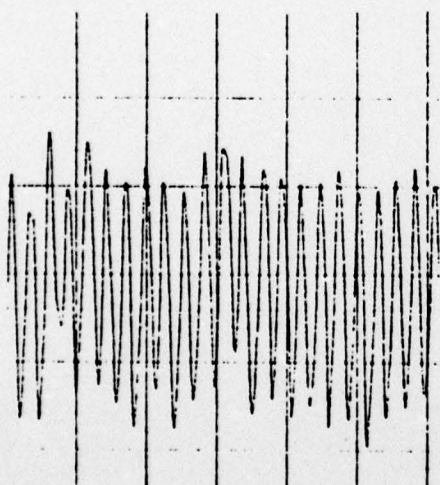




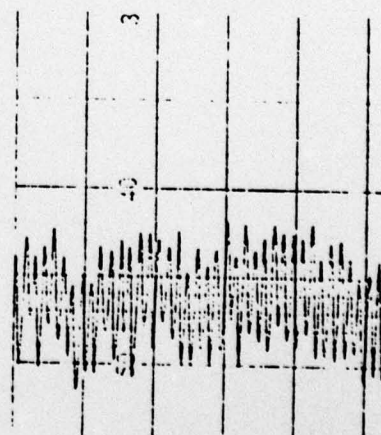
0.61 Hz



1.22 Hz



2.44 Hz



4.88 Hz

Figure Captions

Figure 1. An electric current flowing through mercury droplets interacts with a magnetic field to produce a pressure.

Figure 2. A device for separating gas samples from a flowing mercury-gas stream and inject them into a carrier gas.

1. mercury-gas stream inlet
2. carrier output to column
3. carrier gas inlet
4. mercury reservoir outlet
5. mercury reservoir
6. mercury-gas separation tube.

Figure 3. The mercury drop-gas sample maker section

1. mercury reservoir
at 2 m. pressure
2. pressure controlled
nitrogen source
3. sample introduction
dilution cell
4. flow controller
5. Teflon "T" junction
(bubble maker)
6. Teflon stopcock
7. mercury restrictor
8. coiled buffer tube
9. outlet to linear DC
motor

Figure 4. The linear DC motor for pumping mercury droplets.

1. magnetic pole
2. Teflon tube with copper wire
electrodes
3. inlet from mercury-gas
sampler
4. outlet to mercury-gas
separator
5. phototransistor
6. light emitting diode
7. interrupt line to computer

Figure 5. The gas sample injection section

1. inlet from linear DC motor
2. outlet to chromatographic column
3. Teflon stopcock
4. mercury drain
5. gas-mercury separator

Figure 6. Copper wire sewn through Teflon tube to make electrical contact with the mercury droplets.

Figure 7. Flame ionization detector output at several different input frequencies.